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ELECTROCONDUCTIVITY OF FERROMAGNETICS AT LOW TEMPERATURES

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1. In one of the recent works of the author [1] it was shown that in order to describe the properties of ferromagnetic (conversion) metals it is reasonable to use an ideal model in which a different treatment is made of the "externalness" of conduction s-electrons and the "internalness" of d-electrons. In particular, such a model gave the possibility of establishing the temperature function of electrical resistance of a ferromagnetic near Curie's point.

The present work attempts to obtain the temperature dependence peculiar to the ferromagnetic part of electrical resistance, which determines its particular magnetic nature (spontaneous magnetization). In addition, the calculations are limited to the region of low temperatures far from Curie's point where the value of spontaneous magnetization is very close to saturation. According to the accepted model, spontaneous magnetization is due to the positive conversion effect of internal d-electrons, the states of which are described by the usual method employed in the quantum theory of ferromagnetism [2-4]. The conduction-electron state is described by means of Bloch's monoelectron model.

In ordinary (nonconversion) metals it is reasonable to assume that the cause of electrical resistance is the interaction of conduction-electrons with the thermal oscillations of the ions in the crystal lattice ("phonons"). The collision processes between electrons and phonons determine the temperature dependence of the electrical resistance of a metal. But in the case of ferromagnetic (conversion) metals it is completely valid to assume that, along with these collision processes of electrons and phonons, the processes of direct conversion of the energy of conduction-electrons to the energy of ferromagnetism also takes place. In the accepted model, these conversion processes are naturally described as collisions between conduction-electrons and "spin-waves" of ferromagnetic electrons, introduced first in Bloch's theory of metals [2].

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In the "corpuscular language," the spin-waves can be called "ferromagnons," which technical term we hold to below. Akhiezer and Pomeranchuk [5] introduced the "magnon" concept for paramagnetics; however, these "particles" obey Fermi's statistics when they are spin-waves, as introduced by Bloch for ferromagnetics, and also obey Bose's statistics and therefore they should be called not simply magnons but, for example, ferromagnons).

Given below, according to the model assumed by us, is the calculation of the additional electrical resistance of a ferromagnetic at low temperatures, based upon the calculation of the collisions between conduction-electrons and ferromagnons.

2. According to Holstein and Primakoff [6], the energy of ferromagnetic electrons is described as the sum of energies of "elementary disturbances" thus:

$$E_k = \text{const} + \sum_k n_k \epsilon_k, \quad (2, 1)$$

where

$$n_k = 0, 1, 2, 3, \dots \quad (2, 2)$$

is the number of ferromagnons with the given value of the wave vector k , and

$$\epsilon_k = 2 \dots I d^2 k^2 \quad (2, 3)$$

is the energy of a ferromagnon with this same value k (z is the number (coordination) of the closest neighbors in the crystal lattice of the ferromagnetic; σ is the spin of the atom; I is the conversion integral; and d is a parameter of the lattice). (Note: the expression $\hbar^2 d^2 \sim \hbar^2 / \chi \theta_f I d^2$ determines the effective mass of the ferromagnon and θ_f is Curie's point.)

Since the number of ferromagnons with a given wave vector may be any value [6], these "particles" obey Bose's statistics; therefore, in the stationary (steady-state) state, the average value of n_k equals:

$$\bar{n}_k = (e^{\epsilon_k / \chi T} - 1)^{-1} \quad (2, 4)$$

(χ is Boltzmann's constant). Formula (2, 4) justifies the assumption concerning the smallness of k , which rests on the basis of conclusion (2, 1) [6], for the case considered here of low temperatures, because, when $\epsilon_k \gg \chi T$, Plank's distribution function (2, 4) practically equals zero and consequently the basic role is played only by those ferromagnons for which $\epsilon_k \leq \chi T$, that is $k \ll 1$, since $T \ll \theta_f \sim 2z I / \chi$. The proper selection of the distribution function (2, 4) assumes that an equilibrial (steady) distribution of energy among the oscillations in a spin-field is determined without consideration of the conduction-electrons. In the given case (in contrast to the case of interaction of electrons and phonons), such an assumption is decided as more justified, insofar as the role of the anharmonic terms in the Hamiltonian of the conversion of interaction [6] is comparatively large, not just when close to Curie's point (where it is unnecessary to talk, even approximately, about any harmoniousness); but, as Akhiezer showed [7], even for low temperatures (100K), the relaxation time, as determined by some "cubic" terms in the energy operator, equals about 10^{-7} sec. We shall not stop for a more detailed analysis of the correctness of the assumption concerning the realization of (2, 4), because this is beyond the scope of the present article; however, it is necessary to note that even a contrary assumption concerning the incorrectness of (2, 4) would lead, even in the ordinary theory of "phonon resistance" [4], to a similar temperature dependence of electric dependence, as obtained below.

We shall now investigate the interaction energy between conduction-electrons and the spin-field. We shall regard the state of full saturation as the nondisturbed state. The wave function of the s -electron in this state possesses the usual properties of an eigenfunction belonging to Bloch's electron in an ideal lattice; that is, it is characterized by the value of the k vector of quasi-impulse, which determines the electron state. Thus, for a homogeneous

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distribution of spins in a crystal, that is, in the absence of elementary disturbances of a spin-field, generally no conversions are produced which may lead to additional electrical resistances (except that dependent upon interaction with phonons). Such conversions may be caused only during the presence of inhomogeneity in the spin-moment distribution. Consequently, in the first approximation it can be assumed that the interaction energy of conduction-electrons and ferromagnons is a linear function of the first derivatives of the vector-spin components. From this "linearity" it immediately follows that for each process of interaction between spin-field and conduction electrons the quantum number n_k increases or decreases by unity; that is, this process represents the act of emission or absorption of one ferromagnon during electron conversion from the state $\vec{\xi}$ to the state $\vec{\xi}' (\neq \vec{\xi})$. During acts of emission and absorption of a ferromagnon of impulse \vec{k} , the laws of conservation of quasi-impulse $\vec{\xi}' = \vec{\xi} \pm \vec{k}$ must correspondingly be satisfied.

Inasmuch as possible, we shall try now to clarify the intersection mechanism between conduction-electrons and ferromagnons. The emission of one ferromagnon is equivalent to an increase in magnetization of a body, but absorption is equivalent to a decrease. It is possible to represent, for example, that conduction-electrons undergo magnetic spin-orbital interaction, during which the spin of the whole system (and, consequently, the resulting magnetic moment) is not an integral motion and therefore does not have to be conserved during each act of collision of an electron with a ferromagnon. Therefore, among those conversions leading to emission or absorption of a ferromagnon, those conversions are possible for each one of which the spin of a s-electron does not change its direction to the opposite direction. But, of course, those conversions are possible that conserve the full spin of the system. For example, in the case examined by us earlier [1] of the processes of s-d interchange for each act of emission or absorption of a ferromagnon, the spin of an s-electron must correspondingly reverse its direction in order that the summed moments remain constant. A priori, there are two possibilities:

(1) The energy I of s-d interchange is large compared to the average thermal energy; that is $I \gg kT$. But when the conversions of s-electrons with "turning-over" of the spin are unimportant, because of the impossibility of satisfying the law of conservation of energy, since, as already shown, during low temperatures (which alone are of interest to us), then the number of ferromagnons with energies considerably exceeding kT is insignificantly small and also the minimum possible variation in energy of an s-electron with "turned-over" spin equals: $\varepsilon(\vec{\xi}') - \varepsilon(\vec{\xi}) = I \gg kT \sim \varepsilon_k$.

(2) Exchange energy $I \ll kT$. In this case, conversions with change in spin direction to the opposite direction do not differ at all from conversions without such changes in direction.

These considerations do not generally permit, in the following calculations, one to stipulate whether or not in the processes of emission or absorption of a ferromagnon any change takes place in the spin-orientation of a conduction-electron to the opposite direction. Hereafter, therefore, we shall consider the conduction-electron as a single-valued function of the quasi-impulse $\vec{\xi}$.

3. By employing the usual methods standard in the theory of electro-conductivity [4, 8, 9], it is possible easily to obtain and to solve the kinetic equations of the problem studied.

As a result of ordinary mathematical operations, it is easily found that the right-hand part of the kinetic equations appear to be a linear combination of the following integrals:

$$\frac{1}{kT} \int_0^\infty \frac{k^2 dk}{(e^{k^2/kT} - 1)} \int_0^\infty \frac{d\varepsilon}{(e^{(\kappa - \varepsilon)/kT} + 1)(e^{(\varepsilon - \varepsilon_k - \kappa)/kT} + 1)} \quad (3.1)$$

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$$\chi T \int_0^{\infty} \frac{k^2 dk}{(e^{\epsilon_k/\chi T} - 1)} \int_0^{\infty} \frac{d\epsilon}{(e^{(\mu - \epsilon)/\chi T} + 1)(e^{(\mu - \epsilon - \epsilon_k)/\chi T} + 1)} \quad (3,1')$$

where μ is the chemical potential and ϵ is the energy of the s-electrons. It is easy to see that both integrals in (3, 1) are proportional to T^3 . Consequently, the additional electrical resistance of a ferromagnetic dependent upon the interaction of conduction-electrons with ferromagnons during low temperatures varies in proportion to T^2 .

The dependence, established above, of the additional electrical resistance upon temperature can be obtained also by very general considerations [8]. Just as in the case of electron-phonon interaction during low temperatures, in the conversions discussed above only ferromagnons that have energy $\epsilon_k \leq \chi T$ are involved. The change in energy of an s-electron during collisions equals $|\epsilon' - \epsilon| \sim k$, that is, it is a magnitude of the second order of smallness (relative to k). Therefore, when $T \rightarrow 0^\circ K$ it is possible to "connect" the phase points of s-electrons with a surface $\epsilon = \mu$. By virtue of the smallness of the quasi-impulse of ferromagnons k , the quasi-impulses of electrons ξ vary to a small extent also. We may talk, in this manner, about the diffusion of the phase points of electrons on the surface of zero energy $\epsilon = \mu$. The external electrical field F condenses the phase points in a certain part of the phase surface; the thermal motion tends to "smear apart" this condensation. For a given magnitude of F and given temperature T , statistical equilibrium is established.

The diffusion (caused by thermal motion) flow is equal, for this flow, to the effected field F (the latter, for a weak field, is proportional to the magnitude of this field). The flow from the field will be greater, the slower the condensation of the phase points scatters due to diffusion. The diffusion current is proportional to the derivative of the coefficient of diffusion D times the gradient of the surface concentration of phase points of electrons, which equals the current density in a given direction (equals the difference between the phase points densities in the given direction $\nabla \xi$ for $F \neq 0$ and $F = 0$). Thus, the coefficient of diffusion, with an accuracy equal to that of purely mechanical coefficients of proportionality, appears to be a measure of electrical resistance and in each case the total temperature dependence of the latter is included in D .

From general kinetic considerations it is known that $D \sim \lambda v$, where λ is the length of free path and v is the average velocity for a given case of phase points. Length λ equals the average variation of quasi-impulse of an electron, that is $\lambda \sim |\Delta \xi| \sim k$, and the average velocity v equals the derivative of the "number of collisions" in a unit time of equal probability W times λ ; that is, $v \sim W \lambda$. In determining the value of W , we note that since, at low temperatures, the ferromagnons are excited with small k , then W is of the same order of magnitude as the energy density of these ferromagnons. The ferromagnons take part in the collisions, the energy of which satisfies the law of conservation; moreover, in accordance with Bose's distribution we have $\epsilon_k \sim k^2 T$. Therefore, the number of ferromagnons equals the number of phase points lying in the surfaces $\epsilon(\xi \pm k) - \epsilon(\xi) \pm \epsilon_k = 0$ in the regions bounded by the closed curves $\epsilon_k = k^2 T$. For small k , these curves may be considered as flat circles whose area is approximately k^2 . Consequently, the energy density of ferromagnons taking part in conversions is proportional to $\sim \epsilon_k k^2$ or in virtue of (2, 3) to $\sim k^4$. Thus, for the coefficient of diffusion we obtain $D \sim v \lambda \sim W \lambda^2 \sim k^6$. But in virtue of the condition $\epsilon_k \approx k^2 \approx k^2 T$ we have $D \sim T^3$; consequently the additional electrical resistance of a ferromagnetic, caused by collisions with ferromagnons and based on these very general observations for low temperatures, must vary approximately as T^2 .

4. Thus, the electric resistance of purely ferromagnetic metals (devoid of admixtures and of deformations of the lattice) at low temperatures may be expressed as the sum of three terms thus: $\alpha T + \beta T^2 + \gamma T^3$ where the first term

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(T^5) represents the ordinary phonon part of the resistance; the second term (T^3) is the ferromagnon part discussed above; and finally the third term (T^2), according to Landau and Pomeranchuk [9] (see also [10]), is due to the collisions between electrons. We shall not discuss here the problem concerning the "interference" of these three mechanisms, enumerated above, with each other and with the residual resistance due to the disturbances in the correct alignment of the crystal lattice, which (interference) may lead to additional terms in the expression for electrical resistance, besides its own temperature dependence [11].

As for comparisons with experiments, unfortunately it is necessary to state here the absence of any empirical data on the variation of electric resistance of ferromagnetic substances at low temperatures (down to very low temperature less than 1°K), which would appear a criterion of accuracy for the above-deduced theoretical formulas. Nevertheless, it seems to us that the result obtained above for the temperature function of the ferromagnon part of electric resistance appears to be of nontrivial theoretical interest.

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